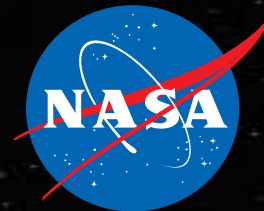


National Aeronautics and Space Administration  
Marshall Space Flight Center



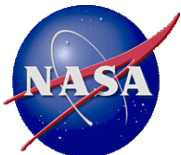
# **Key Quality Assurance Metrics in Additive Manufacturing**

**Doug Wells  
NASA MSFC  
Huntsville AL**

**NASA Quality Assurance in Additive Manufacturing  
A Workshop on Assuring AM Product Integrity**

**Beckman Auditorium, Cal Tech  
Pasadena, CA**

**October 11-12, 2016**

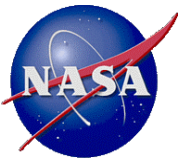


# Summary of Points

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1. Assuring AM product integrity requires process control rigor:
  - Clear definition of the AM process and its metrics
  - Continuous evaluation of the AM process relative to metrics
2. Open loop AM technologies rely upon passive observation of metrics or post-build evaluation of witness specimens
  - Evolving AM monitoring technologies will provide better methods
3. Selected key metrics within the AM process
  - Qualified Metallurgical Process Record
    - Foundational
    - Defines key metrics for evaluation of the process
  - Witness testing for process control
    - Needs to be adequate and intelligent



# Standardization for AM Qualification



National Aeronautics and  
Space Administration

George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812

MSFC-STD-xxxx  
REVISION: DRAFT 1  
EFFECTIVE DATE: Not Released

EM20

MSFC TECHNICAL STANDARD

## Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.  
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—  
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS  
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Release target:  
December 2016

- Draft NASA MSFC Standard
- Methodology for qualification of AM parts and processes for critical applications
  - Space Launch System
  - Commercial Crew Program



Aerojet Rocketdyne RS-25

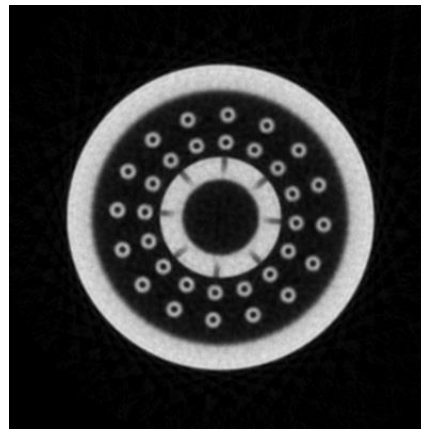


SpaceX SuperDraco

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:



Metallurgical  
Process  
Control



Part  
Process  
Control



Equipment  
Process  
Control



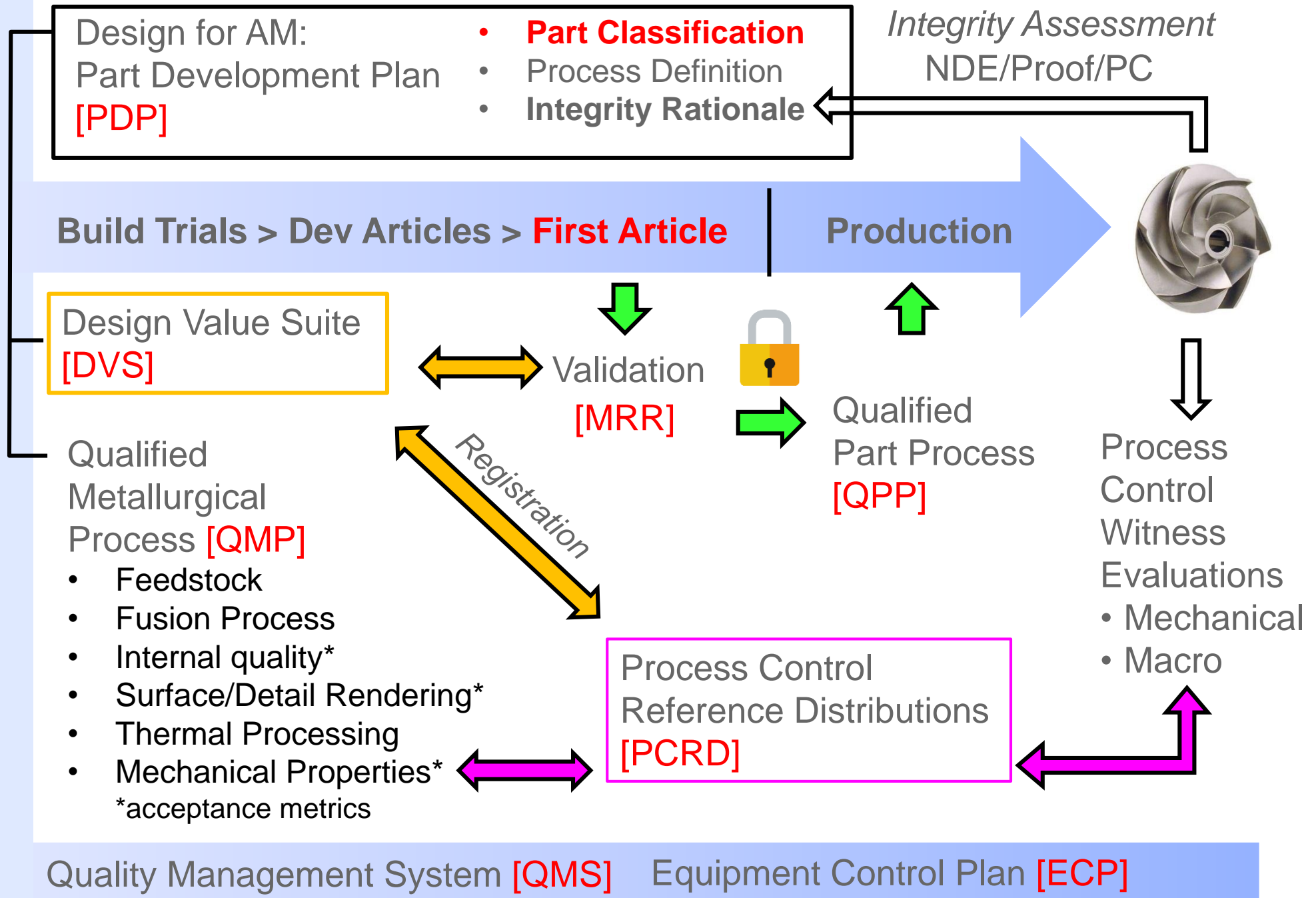
Build Vendor  
Process  
Control

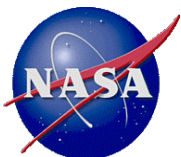
- Each aspect of process control has an essential role in the qualification of AM processes and parts and certification of the systems in which they operate.
- The standard provides a **consistent framework** for these controls and provides a **consistent set of review/audit products**





# Overview of AM Standard





# Products of the Standard

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PDP = Part Development Plans (Overview and implementation)

- Communication, convey risk
- Classification and rationale

DVS = Design Value Suite (properties database)

- “Allowables,” integrated through PCRDs

**QMP** = **Qualified Metallurgical Process** (foundational control)

- Analogous to a very detailed weld PQR

**PCRD** = **Process Control Reference Distribution**

- Defined reference state to judge process consistency

FAI = First Article Inspection

MRR = Manufacturing Readiness Review

QPP = Qualified Part Process

- Finalized “frozen” part process

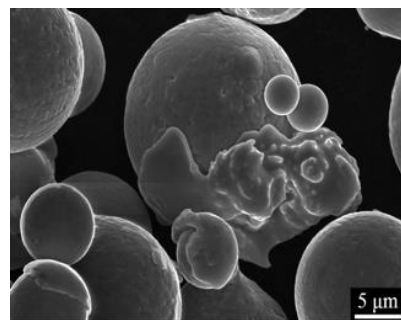
ECP = Equipment Control Plans

- Machine qual, re-qual, maintenance, contamination control

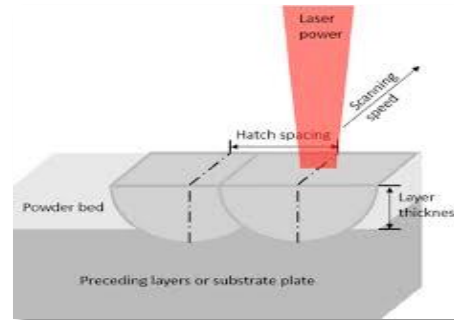
QMS = Quality Management System

- Required at AS9100 level with associated audits

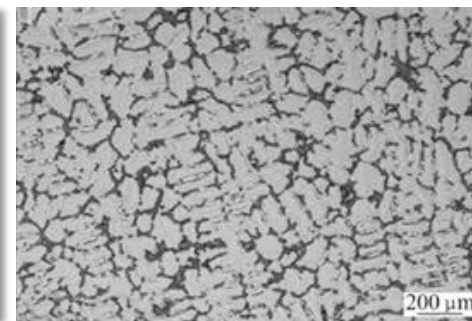
- Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on **every** individual AM machine
- Developed from internal process specifications with likely incorporation of forthcoming industry standards.



Powder



Process Variables



Microstructure



Properties

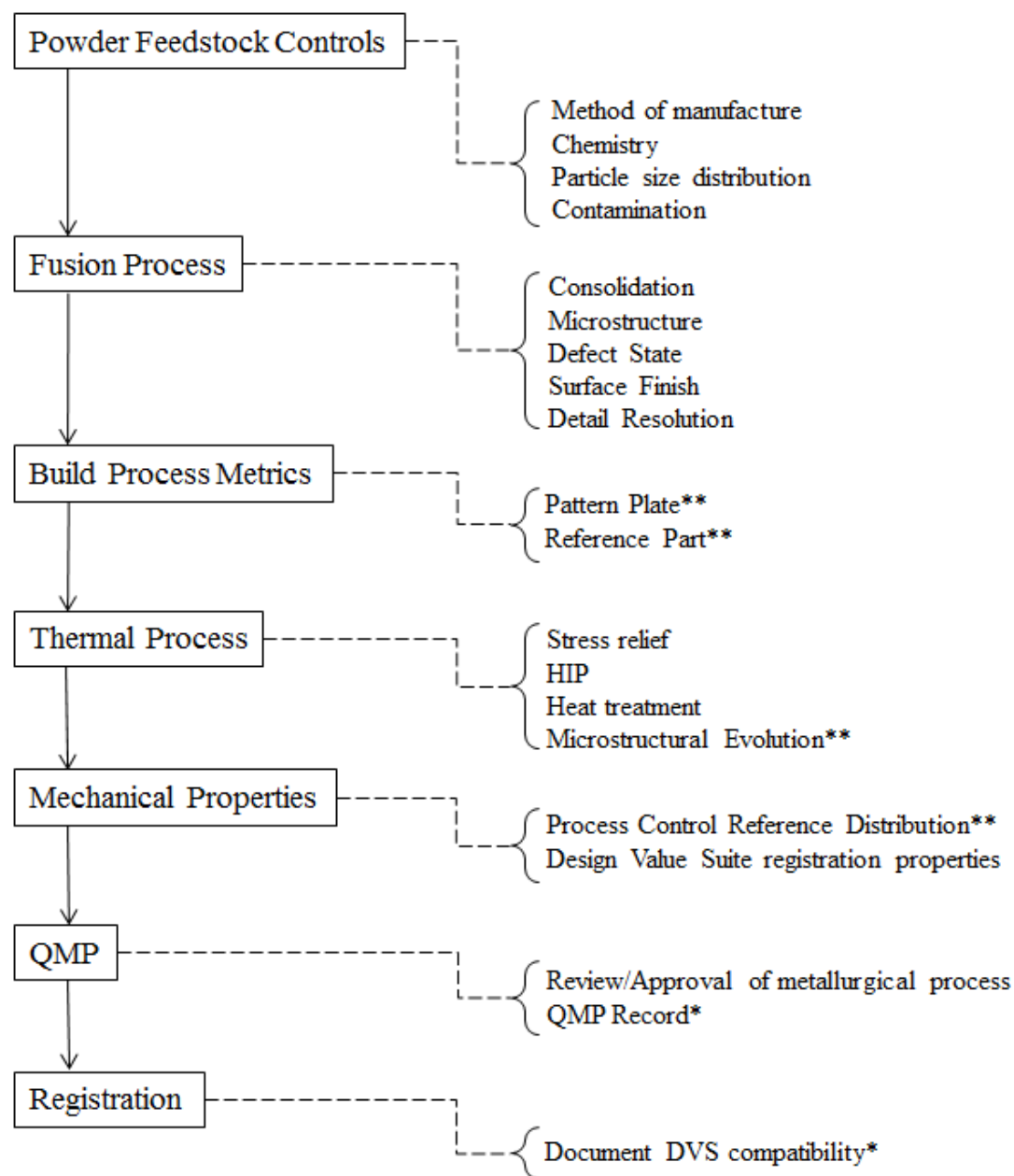


# Foundation: Qualified Metallurgical Process



## Qualified Metallurgical Process (QMP)

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue performance



\*Quality management system record

\*\*Acceptance criteria metric





As Built



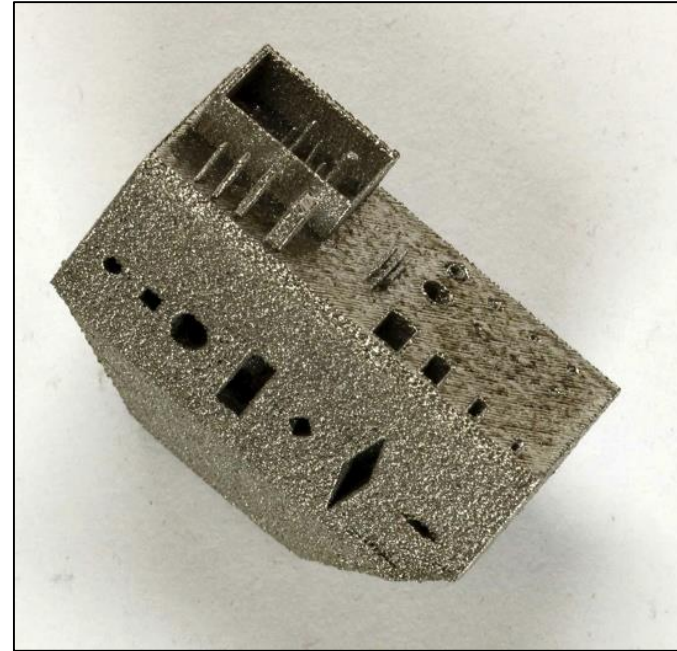
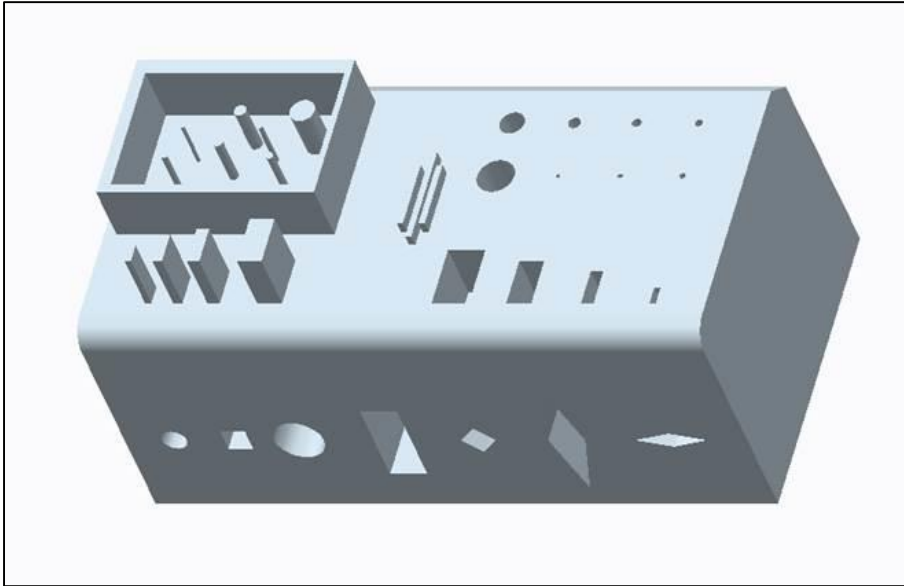
Stress Relieved



HIP & Final

## Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution



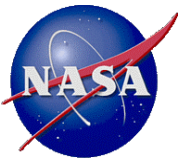
Reference parts:

Metrics for surface texture quality and detail rendering

Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

## Qualified Metallurgical Process (QMP)

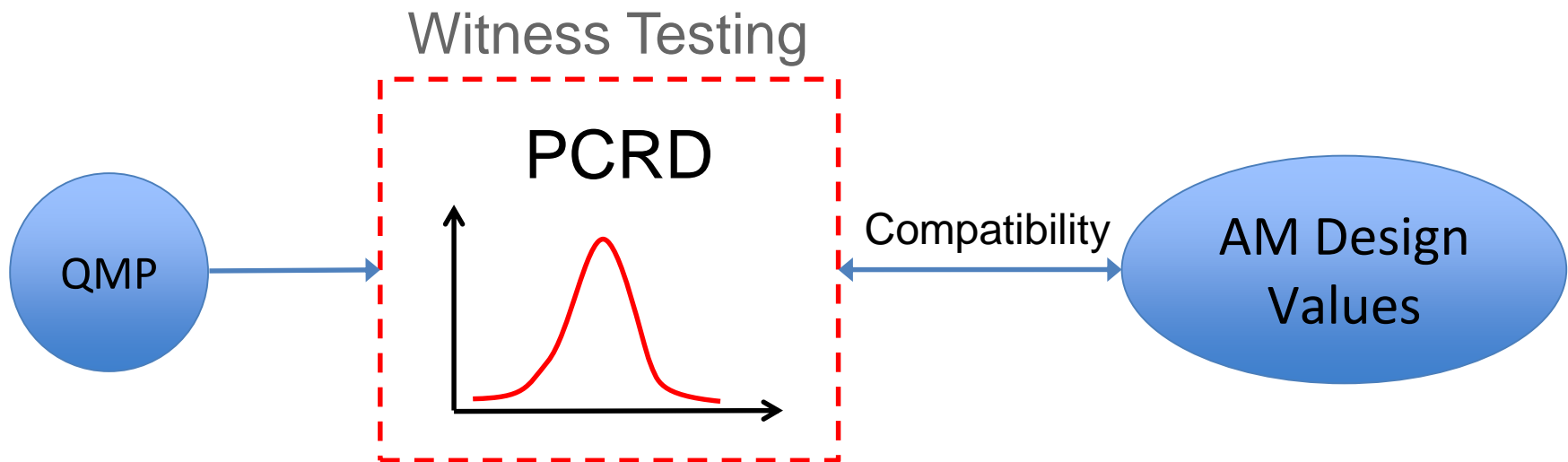
- Reference Parts
- Control of surface finish and detail rendering
- Critical for consistent fatigue performance if as-built surfaces remain in part

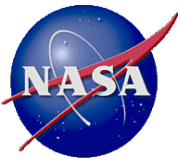


# Foundation: Qualified Metallurgical Process



- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - **Process Control Reference Distributions (PCRD)**
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  - May evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria





# Foundation: Qualified Metallurgical Process

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## Types of AM build witness specimens

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties (as needed)

## What is witnessed?

- Witness specimens provide direct evidence only for the **systemic health of the AM process** during the witnessed build
- Witness specimens are only an **in-direct indicator of AM part quality** through inference.



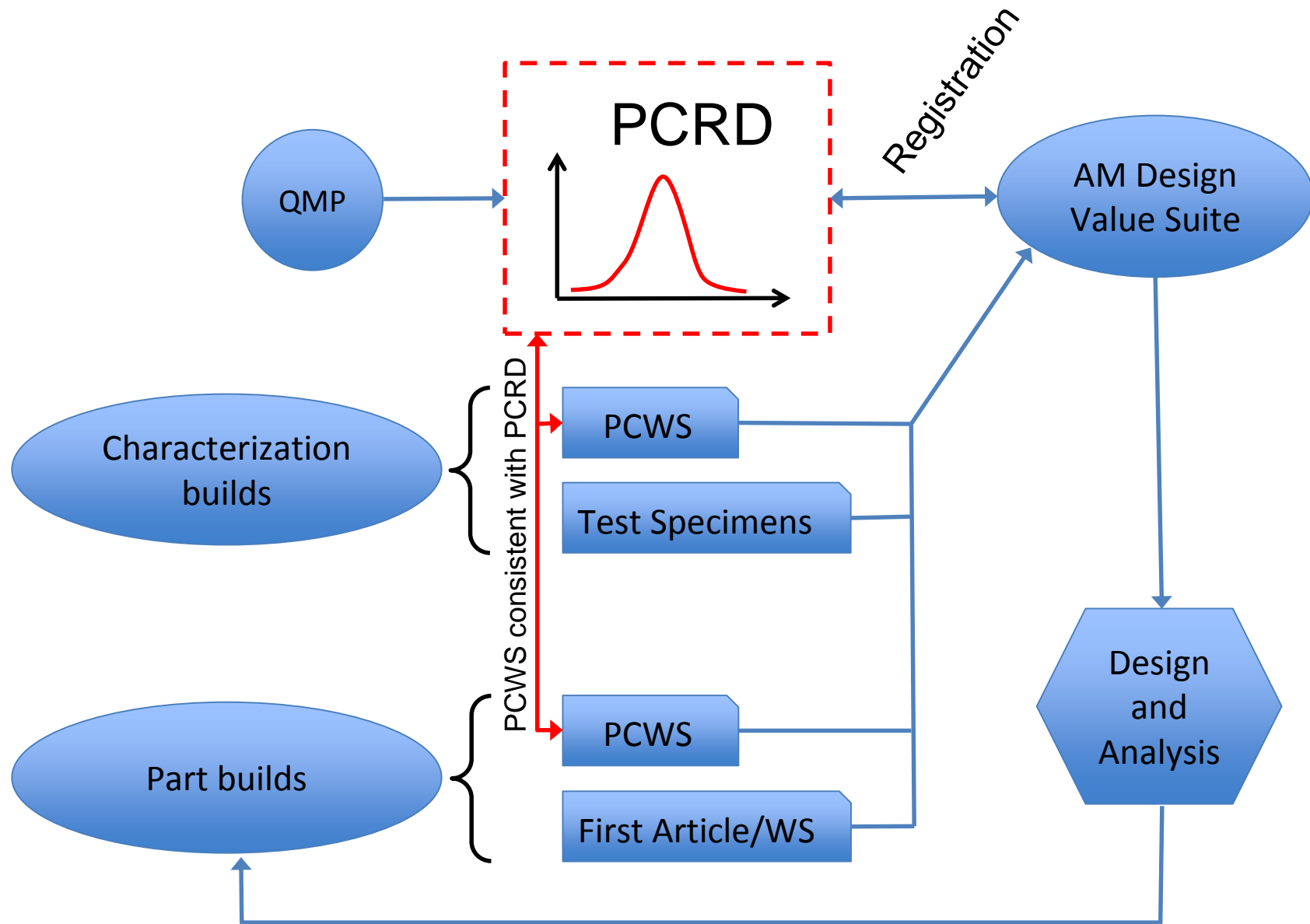
## Mechanical Property Witness Procedures

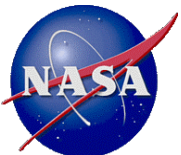
- Move away from spot testing for acceptance against 99/95 design values or specification minimums
- Evaluate with sufficient tests to determine if the AM build is within family
- Compromise with reasonable engineering assurance
- Proposed
  - Six tensile
  - Two fatigue

## Evaluate against the PCRD of the QMP

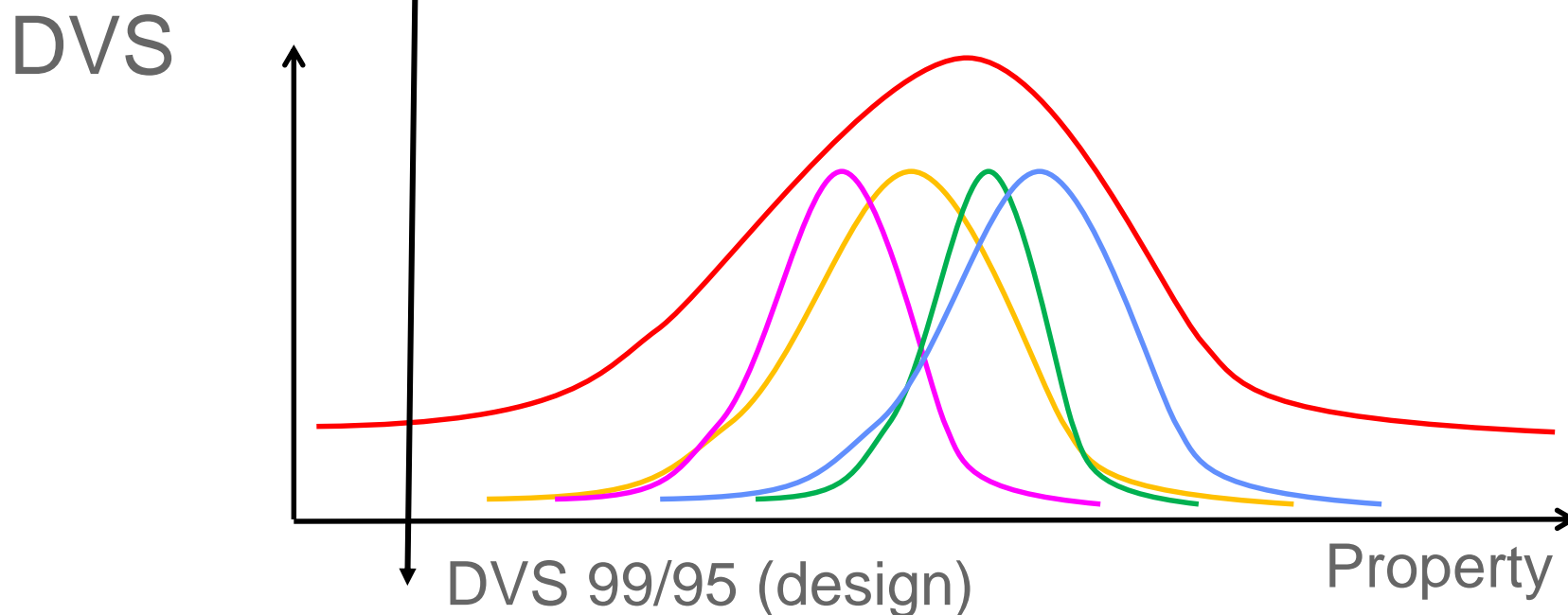
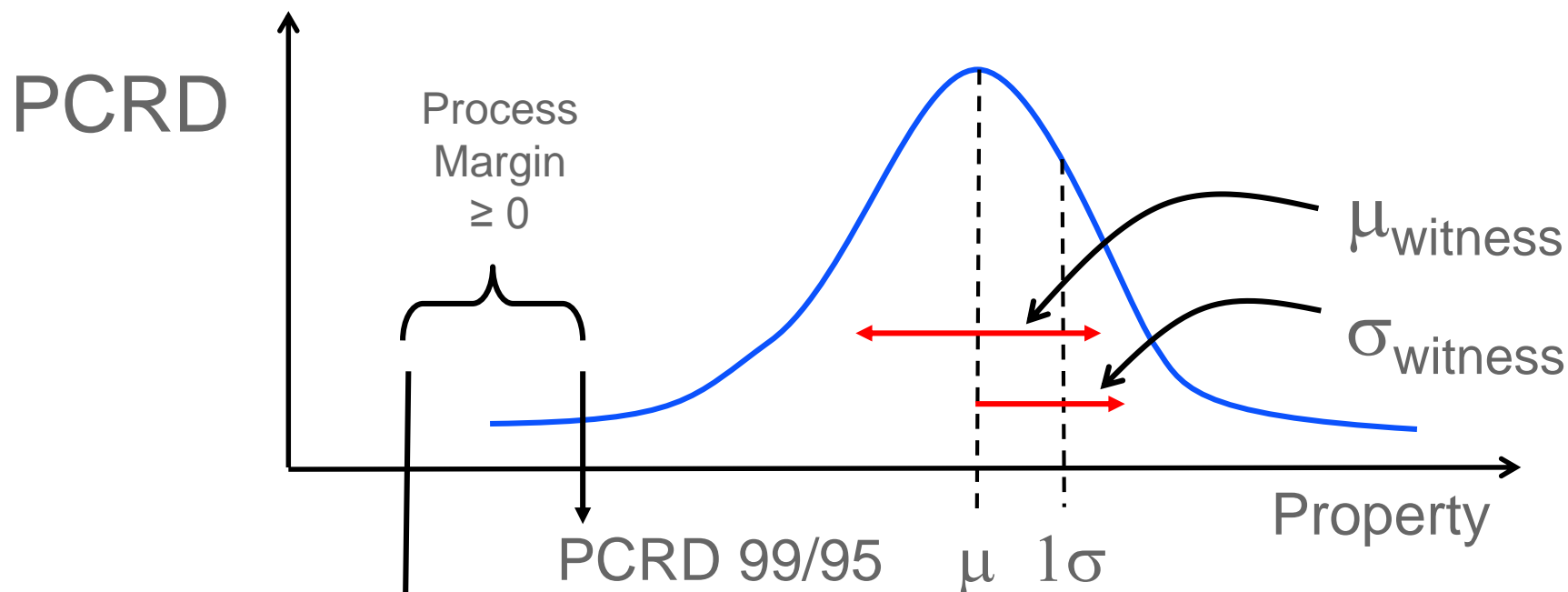
- **Ongoing evaluation of material quality substantiates the design allowable**
- **Only plausible way to maintain design values**





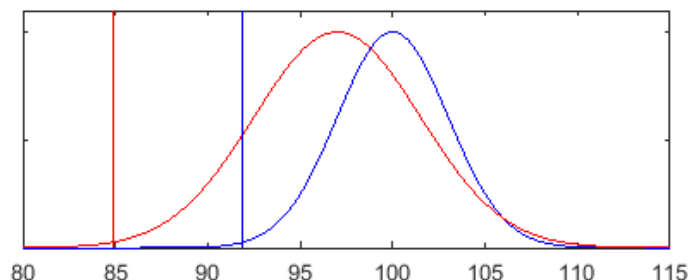


# Foundation: Qualified Metallurgical Process

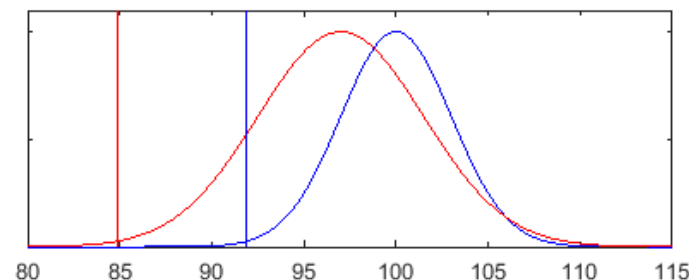


## Example of AM build witness specimen evaluations

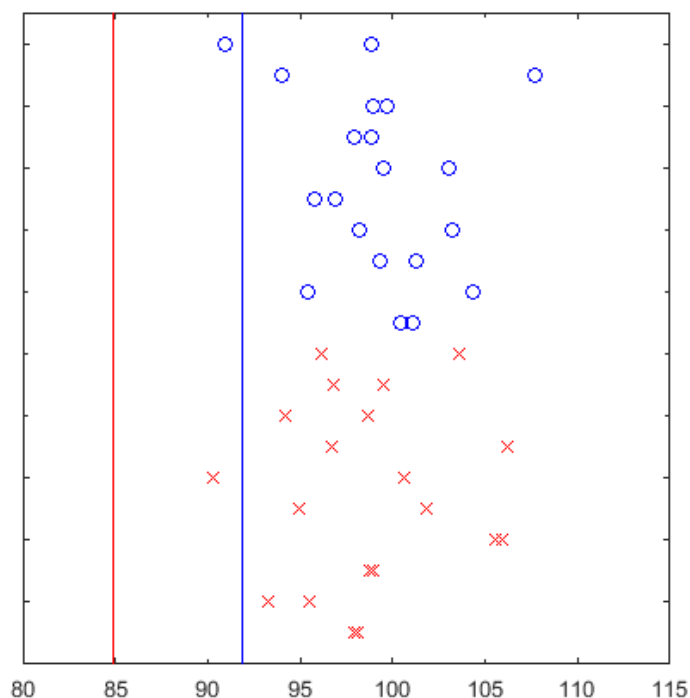
Nominal process is **blue**, off nominal in **red**



Two (2) witness tests per build



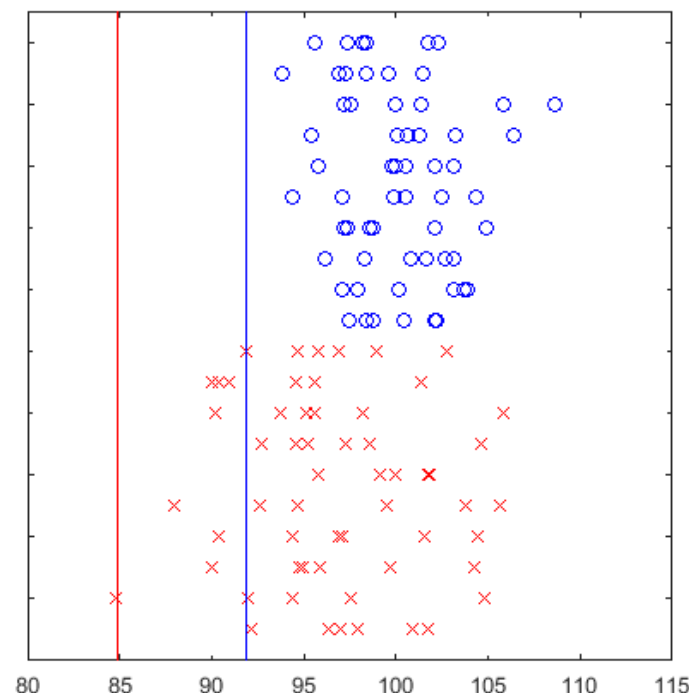
Six (6) witness tests per build



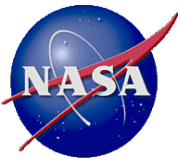
Process shift hard to discern

Random  
draw from  
nominal  
process 10  
times

Random  
draw from  
off-nominal  
process, 10  
times



Process shift discernable with  
analysis of mean and variation



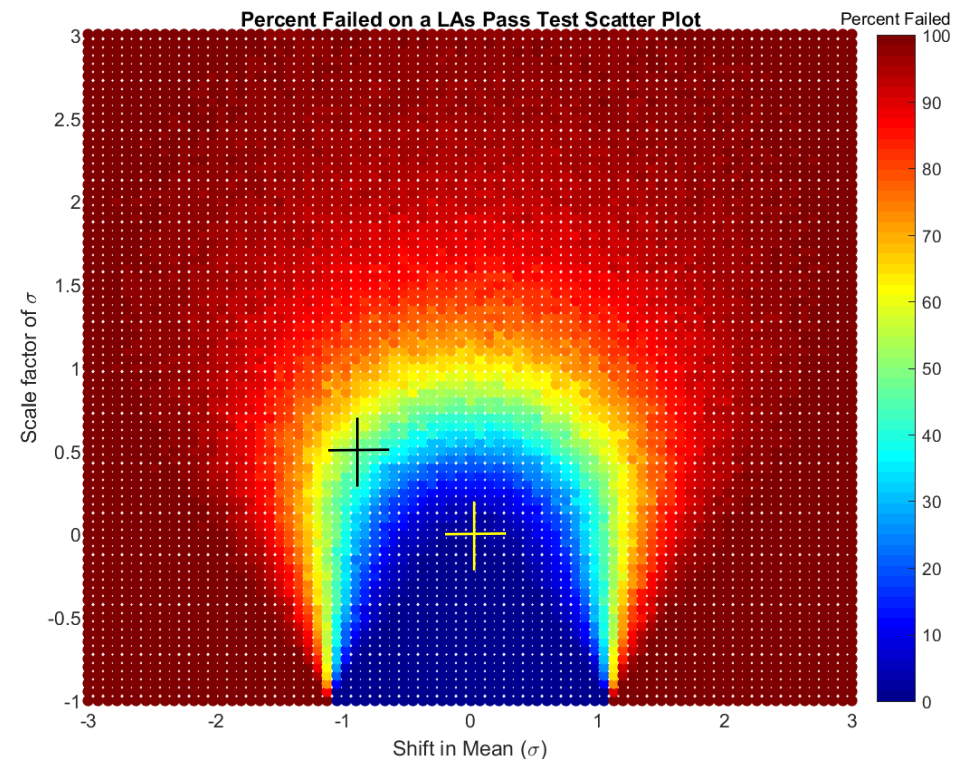
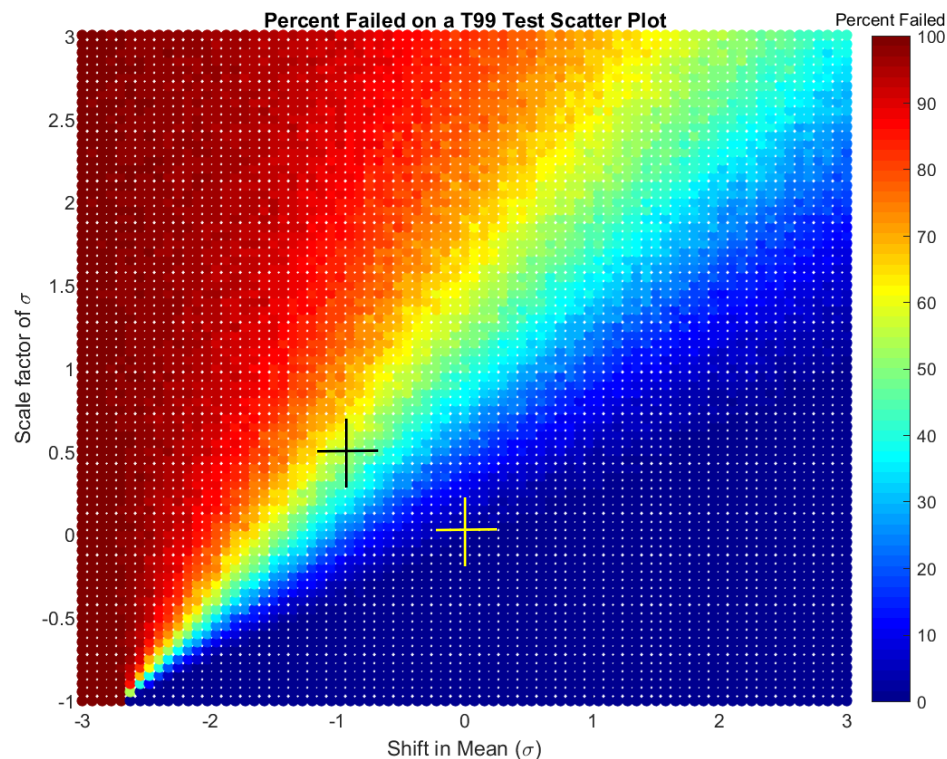
# Witness for Statistical Process Control



Simulation is used to evaluate small sample statistical methods for witness specimen acceptance

Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values





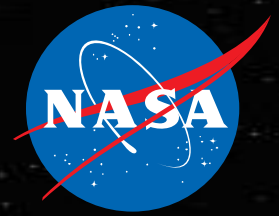
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# Thank You

## Additive Manufacturing at MSFC

